MULTIMEDIA UNIVERSITY

STUDENT ID NO

MULTIMEDIA UNIVERSITY

FINAL EXAMINATION

TRIMESTER 2, 2015/2016

EEN7026 – SEMICONDUCTOR PHYSICS AND MATERIALS

5 MARCH 2016
2.30 p.m. - 5.30 p.m.
(3 Hours)

INSTRUCTIONS TO STUDENTS

1. This Question paper consists of 8 pages with 6 Questions only.
2. Attempt **All** questions. The distribution of the marks for each question is given.
3. Please write all your answers in the Answer Booklet provided.

Useful constants and coefficients:

Physical Constants

Boltzmann's constant (k)	1.3807×10^{-23} JK^{-1}
	8.617×10^{-5} eVK^{-1}
Planck's constant (h)	6.626×10^{-34} Js
Thermal voltage@300K kT/e kT	0.0259 V 0.0259 eV
Electron mass in free space (m_e)	9.10939×10^{-31} kg
Electron charge (e)	1.60218×10^{-19} C
Effective density of states in the conduction band for Si (N_c)	2.8×10^{19} cm^{-3}
Effective density of states in the Valence band for Si (N_v)	1.2×10^{19} cm^{-3}
Permeability of free space (μ_0)	$4\pi\times10^{-7}$ Hm^{-1}
Permittivity of free space of free space (ε_0)	8.85×10^{-12} Fm^{-1}
Avogadro's number (N_A)	6.022×10^{23} atoms/mol

Question 1

(a) The Schrödinger's wave mechanics approach is based on the wave-particle duality principle described by the de Broglie relationship between momentum and wavelength and the familiar classical wave equation. The time-independent Schrödinger equation is given by

$$-\frac{\hbar^2}{2m}\frac{\partial^2\psi(x)}{\partial x^2}+V(x)\psi(x)=E\psi(x)$$

(i) Use the Schrödinger wave equation to show that the allowed energy states of an electron in a one-dimensional infinite potential well of length L, where V = 0 for 0 < x < L and V = ∞ elsewhere, is quantized and is given by $E=\frac{\hbar^2\pi^2n^2}{2mL^2}$, where n = 1, 2, 3, ... [6 marks]

(ii) The normalized wave function in the infinite potential well at the ground state is $\psi(x)=\sqrt{\frac{2}{L}}\sin\left(\frac{\pi x}{L}\right)$. Sketch the first three allowed energy levels, the corresponding wave functions and probability distributions for the electron in this infinite potential well. [3 marks]

(iii) Explain what happen if the potential well is finite, that is V ≠ ∞. [1 mark]

(b) The energy of electron, *E*, as a function of its wavevector, *k*, for the one-dimensional simple lattice structure from the Kronig-Penney model is shown in Figure Q1. Draw the E-k diagram in the first reduced zone and in your diagram indicate the energy gaps between the energy bands. [4 marks]

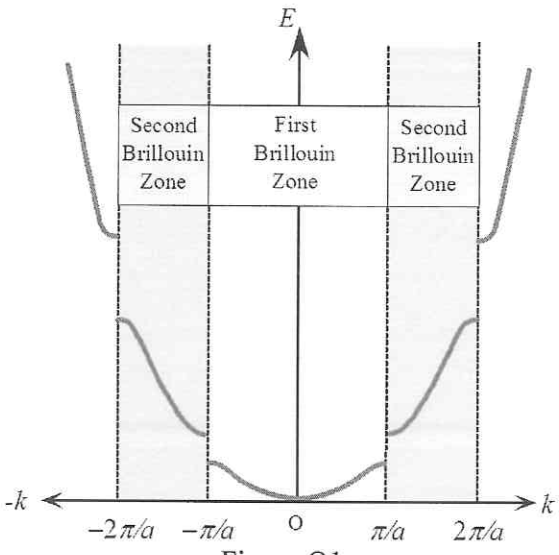

Figure Q1

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Question 2

(a) Figure Q2 shows the diamond lattice unit cell which can be constructed by interpenetrating two face center cubic (FCC) sublattices.

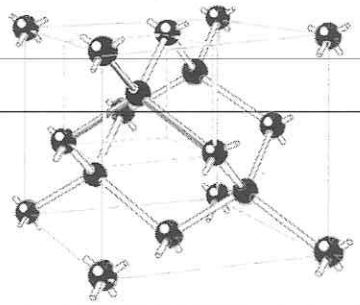

Figure Q2

(i) Determine the number of atoms present in the unit cell. [2 marks]

(ii) Draw the two-dimension (100), (110) and (111) planes in the unit cell and determine the number of atoms on each plane. Which plane has the most number of atoms? [6 marks]

(b) Silicon has the diamond crystal structure with lattice parameter $a = 0.543$ nm and its density is 2.33 g cm^{-3}. When the surface of a Si crystal oxidizes, amorphous SiO_2 layer with a density of 2.27 g cm^{-3} is formed. The atomic masses of Si and O are 28.09 g/mol and 16 g/mol, respectively.

(i) Determine the number of Si atoms per unit volume, in nm^{-3}. [1 marks]

(ii) Determine the number of SiO_2 molecules per unit volume, in nm^{-3}. [3 marks]

(iii) Use your results in (b)(i) and (b)(ii) to estimate how many microns of Si crystal will be consumed to form a 1 micron oxide layer. [2 marks]

(c) With the aid of diagrams, explain the type I and type II semiconductor heterostructures. [4 marks]

Continued....

Question 3

Figure Q3(a) shows the first conduction band and valence bands of GaAs crystal calculated from the pseudopotential method in the first Brillouin zone. The drift velocity of electrons and holes in GaAs and Si as a function of applied electric field is shown in Figure 3(b).

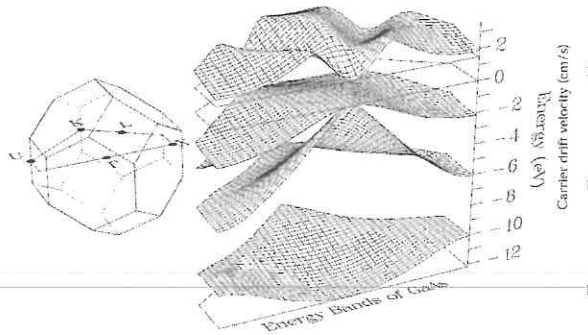

Figure Q3(a)

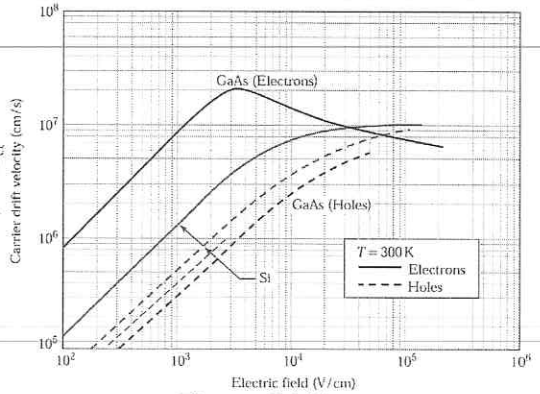

Figure Q3(b)

(a) Show that the complicated band structure of Figure Q3(a) for the electrons or holes in GaAs crystal can be described in a quasi-classical manner in the sense of Newton's law of motion through the use of effective mass given by $m^* = \left(\frac{1}{\hbar^2}\frac{d^2E}{dk^2}\right)^{-1}$.

[5 marks]

(b) Observe the conduction band and the first valence band in Figure Q3(a). Explain which is lower, the hole or electron effective mass near the Γ-point? [2 marks]

(c) Most semiconductors have the conduction band edge at one of the symmetry points in the Brillouin zone. Sketch the constant energy surface near the conduction band edge of semiconductor GaAs, Ge, and Si in three dimensional k-space. Briefly explain your diagrams. [5 marks]

(d) In Figure Q3(b) at electric fields below 10^3 V/cm, the electrons and holes transport in Si and GaAs semiconductors obey the Ohm's law. Use your diagrams in part (c) to explain why the velocity of electrons in silicon is significantly lower as compare to GaAs?

[4 marks]

(e) For electric fields above 3×10^3 V/cm, the velocity of electrons in GaAs decreases with increasing electric field. Briefly explain this phenomenon. [4 marks]

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Question 4

(a) In the effective mass approximation, the donor energy level depends only on the host crystal and the Bohr model-like solution is given by

$$E_d = E_c - 13.6\left(\frac{m_e^*}{m_0}\right)\left(\frac{\varepsilon_0}{\varepsilon}\right)^2 eV .$$

(i) Estimate the energy level below the conduction band edge for donors in GaAs and in Si crystal. Given that the electron effective mass of GaAs is $m_e^* = 0.067m_0$ and the relative permittivity $\varepsilon_{GaAs} = 12.9\varepsilon_0$, the longitudinal and transverse effective mass of silicon are $m_t^* = 0.19m_0$ and $m_l^* = 0.98m_0$, respectively with $\varepsilon_{si} = 11.7\varepsilon_0$. [4 marks]

(ii) The actual value of this energy is found to vary with the size of impurity atoms and only in qualitative agreement with the calculated value. Suggest correction to the model. [4 marks]

(b) In a heavily n-doped semiconductor, the large number of closely packed donor electrons will cause the ionized impurity-electron interaction, electron-electron interaction, and electron-hole interaction that distort both the conduction and valence bands. Briefly discuss how these many-body effects produce band gap narrowing in the semiconductor. [6 marks]

(c) Discuss how one can increase the free electron density in a semiconductor by doping without the presence of ionized impurity scattering? [3 marks]

(d) Consider the two-dimensional representation of the semiconductor GaAs as shown in Figure Q4. If Si atoms are inserted as dopants and exclusively replace Ga atoms in the lattice, will the Si-doped GaAs material be n-type or p-type? Explain your answer. [3 marks]

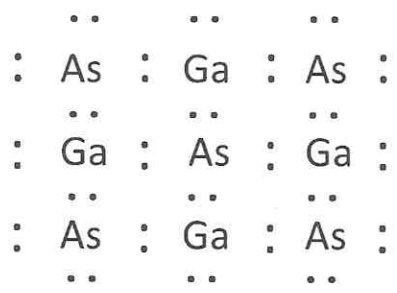

Figure Q4

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Question 5

(a) Czochralski crystal growth is used in almost all the commercial growth of single crystals of Si.

(i) What are the main advantages of the Czochralski method in crystal growth? Name at least two. [2 marks]

(ii) Briefly describe the Czochralski process steps to grow the silicon bulk crystal. [3.5 marks]

(iii) In Czochralski method in crystal growth, which part of a crystal boule will be more likely to be subject to the presence of native defects? Why? [2 marks]

(iv) The Float Zone grown crystal is preferred over that grown by Czochralski technique to fabricate high power devices. Why? [1.5 marks]

(b) Molecular Beam Epitaxy (MBE) is one of the advanced techniques used for epitaxial growth of semiconductors. Briefly discuss this technique and its advantages. [5 marks]

Continued....

Question 6

(a) Si crystal related defects and deep energy levels formation induced by metallic impurities are detrimental to the semiconductor devices.

(i) State three impacts of these defects on semiconductor devices? [1.5 marks]

(ii) Briefly explain the gettering process of reducing or eliminating these impurities. [2 marks]

(b) The density of the point defects is affected by temperature due to thermal vibrations of the lattice atoms. The ratio of the density of the point defects to the density of ideal lattice sites is given by $\frac{N_d}{N_{sites}} = K_d \exp\left(-\frac{\Delta E_d}{kT}\right)$, where the energy needed to generate a point defect in Joule is ΔE_d and K_d is the dimensionless constant. Given that the atomic mass of Si is 28.09 g/mol, the mass density of Si is 2.33×10^6 g/m^3, K_d is 5.5 and the activation energy of the defects is 2.0 eV.

(i) What is the density of point defects in Si at 300 K? Comment your answer. [3 marks]

(ii) Consider a typical dislocation site in Si with 500 missing atoms, calculate the density of dislocations in Si if these dislocations are due to segregation of point defects initially formed at 900 K. [3 marks]

(c) Figure Q6 shows the cumulative gate oxide integrity failures of silicon wafer A and B as a function of oxide breakdown field. Identify the main sources of failures for wafer A and B, respectively. Explain your answer. [4.5 marks]

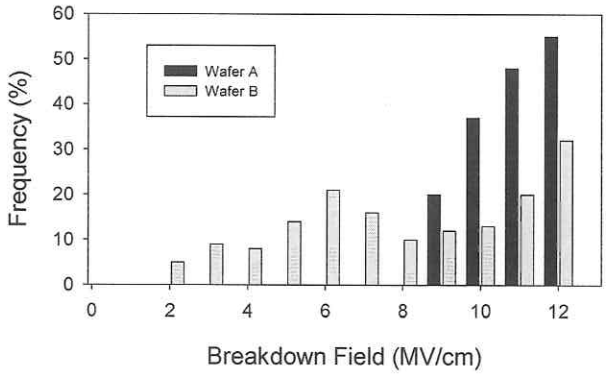

Figure Q6

End of the paper